

Neutrino interactions in astrophysics and the third neutrino mixing angle θ_{13}

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The third neutrino mixing angle θ_{13} is the least known one. In this contribution, after a brief discussion of the current efforts to determine the value of this angle better, various astrophysical implications of a non-zero value of θ_{13} are summarized.

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I. INTRODUCTION

We learned a lot about neutrino-mixing from recent experiments, yet our current knowledge of the third mixing angle, θ_{13} , is very limited. The CP-violating phase δ in the neutrino mixing matrix

$$\mathbf{T}_{23}\mathbf{T}_{13}\mathbf{T}_{12} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & C_{23} & S_{23} \\ 0 & -S_{23} & C_{23} \end{pmatrix} \begin{pmatrix} C_{13} & 0 & S_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -S_{13}e^{i\delta} & 0 & C_{13} \end{pmatrix} \begin{pmatrix} C_{12} & S_{12} & 0 \\ -S_{12} & C_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}, \quad (1)$$

where $C_{ij} = \cos \theta_{ij}$, $S_{ij} = \sin \theta_{ij}$, is likely to be observable only for relatively large values of θ_{13} . Hence it is crucial to have a good idea about the value of this angle if we want to experimentally look for the CP-violation in the neutrino sector, and theoretically examine consequences of breaking this symmetry, such as exploring the origin of the matter-antimatter symmetry in the Universe. In this talk, various implications of a non-zero value of θ_{13} will be briefly summarized.

II. CURRENT LIMITS ON θ_{13}

Current experimental limit on the mixing angle θ_{13} suggested by the Particle Data Group is $\sin^2(2\theta_{13}) < 0.19$ [1] at 90% C.L., based primarily on the Chooz experiment. However, three reactor neutrino experiments, Double Chooz [2], Daya Bay [3], and RENO [4], which currently are at different stages of construction, aim to measure this mixing angle. A measurement of θ_{13} by observing the electron neutrino appearance is also one of the main goals of the T2K experiment [5]. The current T2K run partially coincident with this conference is expected to reach to a sensitivity exceeding the current Chooz limit.

After the publication of the most recent KamLAND results [6] it was noted that best fit values for the neutrino mass difference and mixing angle determined from the KamLAND and solar neutrino data in the two-flavor analysis are not the same [7]. Even though previously undiscovered interactions that distinguish neutrino (those coming from the Sun) and antineutrino (those coming from a reactor) masses and mixings could cause such a difference, the simpler explanation is a non-zero value of θ_{13} . As shown in the Figure 1, finite values of θ_{13} should place the best fit values of the of solar and reactor neutrino data at different locations. Analyses by many authors indeed point out to a non-zero value of θ_{13} (see references [8] through [13]). Care must be taken, however as errors given are non-Gaussian when a non-zero value of θ_{13} is quoted. Most recent low-threshold analysis of both phases of the Sudbury Neutrino Observatory (SNO) suggests $\sin^2 \theta_{13} < 0.057$ at 95% C.L. with a best fit value of $2.00^{+2.09}_{-1.63} \times 10^{-2}$ [14]. One should note that it is not difficult to introduce theoretical models with such large values of θ_{13} [15, 16].

One note of caution is in order, namely that the value of θ_{13} is small. Theoretical input into the analysis of neutrino data includes other small quantities which are not well-determined either. For example neutrino-deuteron cross sections are a crucial input into the analysis of the SNO data. One approach to the calculation of neutrino-deuteron cross sections from the first principles would be using the effective field theory: In this reaction, which is below the pion threshold, the $^3S_1 \rightarrow ^1S_0$ transition dominates and one only needs to determine the coefficient of the two-body counter term, L_{1A} , associated with the isovector two-body axial current, to predict the cross-section [17, 18]. The L_{1A} term can be obtained by either comparing the cross section $\sigma(E) = \sigma_0(E) + L_{1A}\sigma_1(E)$ with the cross-sections calculated using other approaches (save the model dependences [19]) or measured experimentally (e.g. using solar neutrinos as a source). It can be shown that uncertainties coming from the lack of knowledge of θ_{13} and the counter-term L_{1A} in fitting the solar neutrino flux data are comparable [20]. In addition, signatures for non-zero values of θ_{13} may also mimic signatures of physics beyond the Standard Model [21].

A good recent summary the current status and near-term prospects of θ_{13} phenomenology is given in Ref. [22].

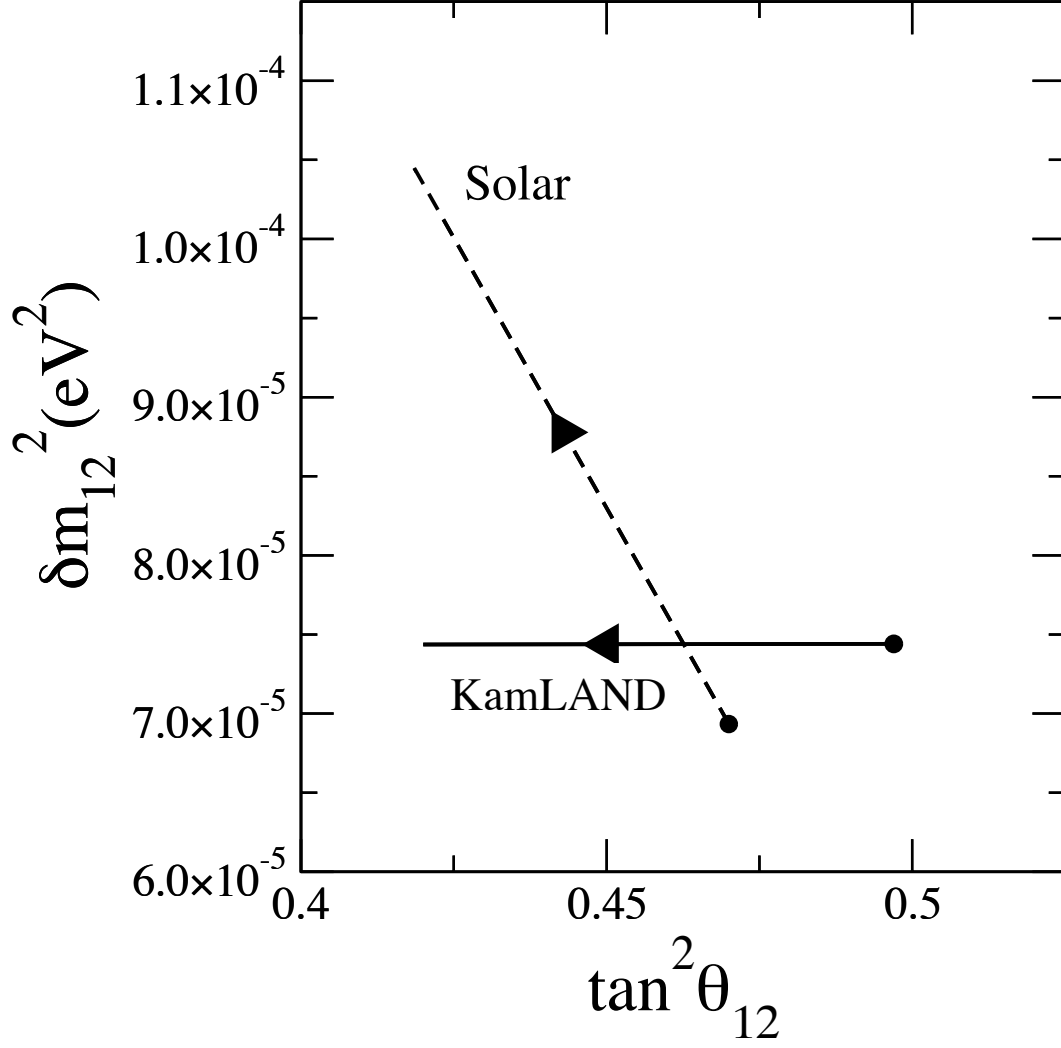


FIG. 1: The change in the best fit values of δm_{12}^2 and θ_{12} with increasing value of θ_{13} . Parameter values corresponding to $\theta_{13} = 0$ are indicated by filled circles. Both for KamLAND and solar neutrino experiments the range $0 \leq \sin^2 2\theta_{13} \leq 0.1$ is shown [7].

III. θ_{13} AND CORE-COLLAPSE SUPERNOVA PHYSICS

Understanding the dynamics of core-collapse supernovae is important not only to better understand later stages of the stellar evolution, but also to ascertain the suitability of core-collapse supernovae as possible sites of the r-process nucleosynthesis. For nuclei with $A \lesssim 100$, r-process abundances observed in the solar system and iron-poor stars agree very well, suggesting a universal site.

Of course understanding the supernova dynamics is not the whole story. To understand the r-process one also needs to understand beta-decays of nuclei both at and far-from stability: Half-lives at the r-process ladder nuclei ($N = 50, 82, 126$), where abundances peak, should be known well. One also needs accurate values of the energies of the initial and final states as well as the matrix elements of the Gamow-Teller operator $\sigma\tau$, (even the forbidden operators $\mathbf{r}\sigma\tau$) between those states. Understanding the spin-isospin response of a broad range of nuclei to a variety of probes is indeed crucial for a wide range of astrophysics applications!

Yields of r-process nucleosynthesis are determined by the electron fraction, or equivalently by the neutron-to-proton ratio, n/p . Interactions of the neutrinos and antineutrinos streaming out of the core both with nucleons and seed nuclei determine the n/p ratio. Hence to understand all the physics associated with the core-collapse supernovae, it is crucial to understand neutrino properties and interactions [23]. Before those neutrinos emitted from the core reach the r-process region they undergo matter-enhanced neutrino oscillations as well as coherently scatter off other neutrinos. Many-body behavior of this neutrino gas is still being explored, but is likely to have significant impact on r-process nucleosynthesis. Possible existence of exotics, such as sterile neutrinos, would also impact supernova dynamics [24].

The MSW potential is provided by the coherent forward scattering of electron neutrinos off the electrons in dense matter via a W-exchange. (There is a similar term with Z-exchange. But since it is the same for all neutrino flavors, it does not contribute at the tree level to phase differences unless we invoke a sterile neutrino). If the neutrino density itself is also very high then one has to consider the effects of neutrinos scattering off other neutrinos. This is the case for a core-collapse supernova. Both the O-Ne-Mg-core collapse and iron-core collapse scenarios should be effected by neutrino-neutrino interactions.

For the illustrative case of two flavors of neutrinos (and no antineutrinos), forward scattering of neutrinos from other neutrinos is described by the Hamiltonian [25]

$$H_{\nu\nu} = \frac{\sqrt{2}G_F}{V} \int d^3p d^3q (1 - \cos \vartheta_{pq}) \mathbf{J}(p) \cdot \mathbf{J}(q). \quad (2)$$

where $\cos \vartheta_{pq}$ is the angle between momenta p and q . In Eq. (2) the "neutrino spin" operators are

$$J_+(p) = a_x^\dagger(p)a_e(p), \quad J_-(p) = a_e^\dagger(p)a_x(p), \quad J_0(p) = \frac{1}{2} (a_x^\dagger(p)a_x(p) - a_e^\dagger(p)a_e(p)). \quad (3)$$

In Eq. (3), "neutrino spin" operators are written in terms of the flavor creation and annihilation operators. It is possible to include all three flavors and antineutrinos in the equations above. Many authors studied neutrino propagation with neutrino-neutrino interactions (see references [26] through [36]). One typically finds large-scale, collective flavor oscillations deep in the supernova envelope, which is sensitive to the value of θ_{13} . Of particular note is the presence of spectral swaps between electron neutrinos and neutrinos of other flavors, which seem to persist even for very small (but non-zero) values of θ_{13} (see references [37] through [39]). Especially for iron-core supernovae, those swap features are present at somewhat lower (i.e. solar neutrino) energies than one usually associates with supernovae.

Since the neutron-to-proton ratio, n/p , or alternatively the electron fraction, is determined by the interactions and the environment-dependent propagation of the neutrinos and antineutrinos streaming out, the value of θ_{13} is an important quantity in determining abundances of r-process elements. Preliminary work suggests that for larger values of θ_{13} , neutrino-neutrino interactions may hinder the r-process by increasing the electron fraction [32] although much work remains to be done.

The value of θ_{13} may also effect light-element production through the so-called ν -process. Yoshida *et al.* found that the cosmological abundance ratio $N(^7\text{Li})/N(^{11}\text{B})$ not only depends on θ_{13} , but this dependence is different for the normal and inverted mass hierarchies [40].

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